Computer-Aided Design of Diode Frequency Multipliers

This article describes the development and use of the MultFreq program for diode multipliers, and provides a practical example

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his article describes a computational tool created to help with the design of reactive and resistive frequency multipliers. With the MultFreq program, calculation of all the inherent parts of this kind of circuit, such as filters and impedance matching networks, can be performed. We also present the multiplier layout, including all calculated dimensions.

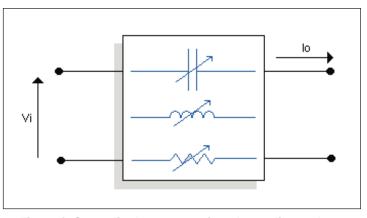
In a telecommunication system, the generation of high stability, low noise specific-frequency signals is important in many applications [1]. A signal of higher frequency is frequently obtained by generating har-

monics from a signal of a lower frequency. This input signal usually comes from a very stable source such as crystal oscillator.

Frequency multipliers can be characterized as devices able to realize this harmonic generation process. Usually, this kind of circuit uses the nonlinear characteristics of some element to provide multiples of a determined frequency. The desired frequency is selected through an appropriate filtering process.

Frequency multiplication can be obtained through passive (diodes) or active (transistors) elements [2]. In this work, the approach used is valid only for reactive and resistive passive multipliers.

The reactive multipliers have restricted use on narrow-band applications. In fact, the reactance is a property linked to the frequency. Consequently, any matching structure used will be efficient at only one frequency. The required nonlinear characteristics can be obtained



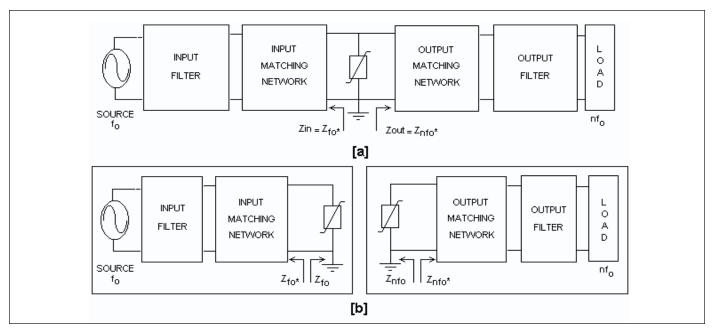
▲ Figure 1. Generalized representation of a nonlinear element.

through a varactor diode or a SRD (Step Recovery Diode). A SRD junction is characterized by a capacitance with a nonlinearity stronger than that shown by a varactor [3].

Reactive multipliers based on varactor diodes are used on low order multiplication of microwave signals. On the other hand, SRDs are useful to provide higher order harmonics in the UHF band and in a microwave narrow band, with an output frequency never higher than 20 GHz [3].

In the resistive case, multiplication through a Schottky diode is characterized by its nonlinear V/I relationship that creates harmonics from an excitation signal. Multiplication using these diodes is based on a nonlinear resistance. Since their characteristics do not vary with the frequency over a significantly wide band, they can be considered as wide-band devices.

Unfortunately, because of their low efficiency, resistive multipliers are less used than the reac-



▲ Figure 2. (a) Multiplier structure. (b) Isolated equivalent circuits at the input and output frequencies.

tive ones. In fact, the efficiency decreases rapidly as the harmonic order increases. For this reason, they are rarely employed to generate harmonics above second order [4].

However, there are three advantages in choosing a Schottky diode: wider bandwidth, high stability (the nonlinear resistance of this element offers considerable prevention against parametric oscillations) and the possibility of employing multipliers at frequencies above 100 GHz [1].

Operating principles of diode frequency multipliers

Harmonics generation is associated with nonlinearity. In general, for any nonlinear component, Figure 1, the output current is a nonlinear function of the input voltage, as follows:

$$i_0(t) = g[v_i(t)] \tag{1}$$

where g is the nonlinear transfer function of this component. Making a Taylor series expansion, [3],

$$i_0(t) = g_0 + g_1[v_i(t)] + g_2[v_i(t)]^2$$
 (2)

where:

$$g_0 = g(0)$$

$$g_1 = \frac{dg}{dV_i}\bigg|_{V_i = 0}$$

$$g_2 = \frac{1}{2} \frac{d^2 g}{dV_i^2} \bigg|_{V=0}$$

Let us consider an excitation $v_i(t) = A \cos(\omega_0 t)$:

$$i_0(t) = g_0 + g_1[A\cos(\omega_0 t)] + g_2[A\cos(\omega_0 t)]^2 + \cdots$$
 (3)

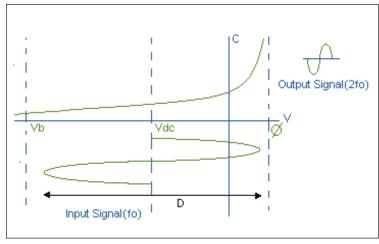
$$\begin{split} i_0(t) &= [g_0 + \, g_2 A^2/2] \, + g_1 [A \, \cos(\omega_0 t)] \\ &+ g_2 [A^2 \, \cos(2\omega_0 t)] + \cdots \quad (4) \end{split}$$

Note that the output current has a DC component, the fundamental frequency and, beyond that, higher order harmonics.

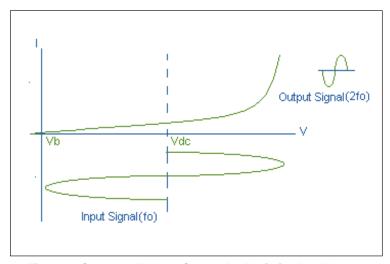
The multiplier circuit should contain, in addition to a nonlinear device, filters capable of selecting the desired component at the output and separating the source from the generated harmonics. The filter connected in the input port of the nonlinear element behaves as an open circuit for all components except for the fundamental frequency (f_0) . At this frequency (f_0) it must present a matching impedance (Zf_0) . At the output port, a similar circuit is connected. However, it must present a matching impedance (Znf_0) at the desired frequency (nf_0) [4].

The block scheme of an nth-order frequency multiplier circuit with a shunt mounted diode is shown in Figure 2a. Dual circuits with series-connected diodes are also frequently used.

From this methodology the multiplier is analyzed as two isolated structures (Figure 2b) operating at different frequencies, but associated by the characteristic equation of the nonlinear element.



▲ Figure 3. Curves CxV and input/output signals.



▲ Figure 4. Current x Voltage Curve of a Resistive Doubler.

General properties of reactive multipliers

In any nonlinear capacitance a set of equations, often called Manley-Rowe relations, determine the power balance among the present signals [5]:

$$\sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \frac{m P_{m,n}}{m f_1 + n f_2} = 0$$
 (5)

$$\sum_{n=0}^{\infty} \sum_{m=0}^{\infty} \frac{n P_{m,n}}{m f_1 + n f_2} = 0 \tag{6}$$

where f_1 and f_2 are the capacitance's excitation frequencies; m and n are harmonic orders of each frequency; and $P_{m,n}$ is the real power at the frequency $\lfloor mf_1 + nf_2 \rfloor$.

In reactive multipliers there is only one excitation frequency, therefore the relations become

$$\sum_{m=0}^{\infty} P_m = 0 \tag{7}$$

where P_m is the real power at the frequency mf_0 and f_0 is the capacitance's excitation frequency.

Equation (7) states that the excitation power can be totally converted to only one harmonic if a unique output signal is generated. This relation denotes the power distribution on the reactive junction only. The power dissipated by the diode's series resistance and the other multipliers losses (filters, impedance mismatch, etc.) must also be added.

All circuit parts are designed to obtain the required harmonic with the best efficiency. A design strategy used in this approach, begins by the use of Burkhardt's method [4]. Based on the choice of the diode and the drive level, this method permits the prediction of output power, bias voltage and efficiency of the multiplier. It also determines the values of diode input and output impedance for maximum efficiency.

In Figure 3, the drive level D defines the excursion of diode's C/V curve by the excitation signal. This parameter determines how large the input power must be to use the nonlinear characteristic as efficiently as possible [1].

In a Schottky-barrier varactor, the maximum possible drive level is D=1. To attain the maximum drive level, the diode junction voltage must use the full range between the breakdown voltage (V_b) and the junction voltage (ϕ) . For other kinds of varactors, D could be larger than one, although the positive excursion will be clamped in $V=\phi$.

General properties of resistive multipliers

The nonlinear characteristic of a resistive multiplier may be represented by the I×V curve of a forward biased Schottky-barrier diode, as shown in Figure 4.

In the case of positive-resistance nonlinear devices, the relations among the power of the present signals are given by the Page theorem [6]:

$$\sum_{m=1}^{\infty} m^2 P_m \ge 0 \tag{8}$$

where m is the component order and P_m is the power at the mth-harmonic.

Equation (8) shows that the power distribution is made according with each frequency component order, and the total power balance is never negative.

When the input power P_1 is the available power from the generator, and all harmonics generated except the nth-harmonic are made null, we obtain:

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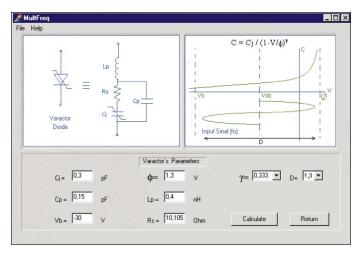


Figure 5. Screen of varactor's input parameters.

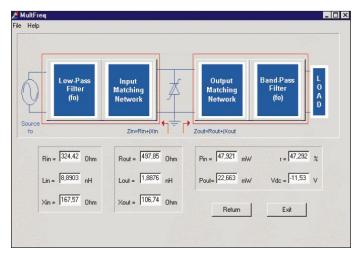
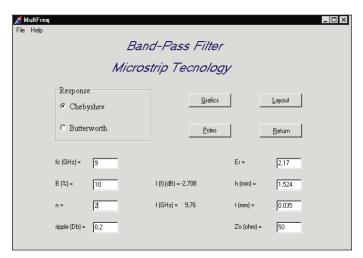


Figure 6. Burkhardt method results and exit to subsequent project sections.



▲ Figure 7. Output filter circuit parameter screen.

$$\left| P_n \right| \le \left| \frac{P_1}{n^2} \right| \tag{9}$$

where P_n is the power of nth-harmonic.

According to equation (9) resistive doubler and triplers have maximum possible efficiencies of 25 percent and 11.1 percent, respectively. This low conversion efficiency is a fundamental limitation on all multipliers using positive nonlinear resistance.

CAD for microwave diode frequency multipliers

The design procedure described here is implemented in the form of a computational tool, called MultFreq, which offers the following features.

- Calculation of circuit parameters such as efficiency, output power, bias voltage, and input and output diode impedance.
- Design of the necessary filters for the isolation of the multiplier ports: low-pass and band-pass filters of Chebyshev and Butterworth types in distributed and lumped parameters.
- Impedance matching networks using series and parallel stubs.
- Design of λ/4 transformers of Chebyshev and Butterworth types providing dimensions and impedance characteristics of each section.
- Multiplier layout in distributed parameters, including all calculated dimensions.
- Simulation in frequency of each circuit block: insertion and return losses.
- Poles and zeros analysis of filters.

As an example, a step-by-step design procedure of a varactor frequency multiplier using MultFreq is outlined below.

- 1) Enter the diode's specifications and the drive level, as illustrated in Figure 5.
- 2) Based on the Burkhardt method and from initial specifications, all project parameters are calculated. These parameters are: efficiency (r), input power $(P_{\rm in})$, output power $(P_{\rm out})$, bias voltage $(V_{\rm dc})$, input $(R_{\rm in}+jX_{\rm in})$ and output $(R_{\rm out}+jX_{\rm out})$ diode impedances at the input and output frequencies.

The Burkhardt method results and the block schematic of the multiplier are shown on the next screen (Figure 6). From this block diagram, it is possible to access the MultFreq's functions that allow the multiplier implementation in distributed parameters.

3) Call the filter design modules and provide the specifications of each filter. Figure 7 shows the input data

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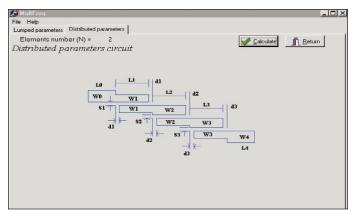


Figure 8. Output filter dimensions.

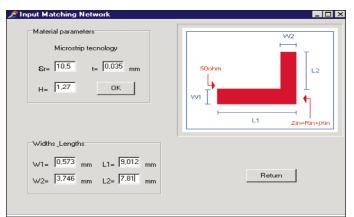
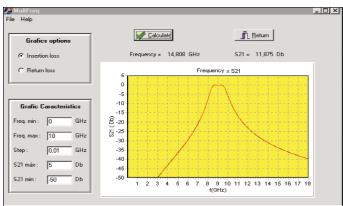


Figure 10. Matching network circuit window.

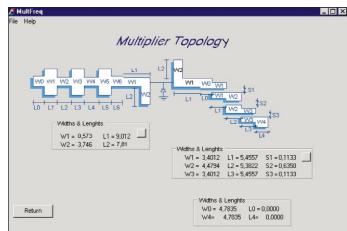
screen of the bandpass filter. The output results are the poles and zeros diagram of the transfer function, frequency responses and the filter topology in lumped and distributed parameters. Figures 8 and 9 show two typical outputs.

- 4) Call the matching network modules and design the input and output matching circuits (Figure 10). Only the substrate characteristics are necessary, because the impedances to be matched are previously defined.
- 5) Finally, with all blocks already calculated, it is possible to view the multiplier layout and to verify the dimensions of all circuit sections (see Figure 11).

To obtain the maximum efficiency, the results from the implemented software are submitted to a computer aided optimization process. Figure 12 shows a varactor frequency tripler designed using MultFreq. Notice the diode's bias structure that consists of a low-pass filter sized to block the propagation of 3 GHz and 9 GHz signals through the bias source.



▲ Figure 9. Frequency response of the output filter.



▲ Figure 11. Reactive multiplier layout.

Conclusion

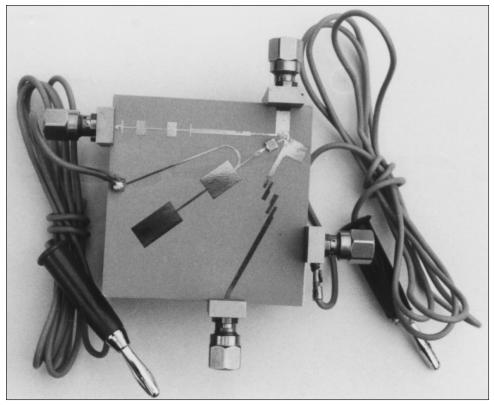
In this article we have presented a useful computational tool developed to aid in the design of frequency multipliers. The multiplier design is accomplished step by step in a multimedia environment that also allows analysis and simulation tools to be used.

The software was tested by designing several multipliers. To obtained the maximum performance, the results were then subjected to an optimization process using the Harmonic Balance technique. We have found good agreement between the theoretical and experimental results, thereby proving the utility of the MultFreq software.

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▲ Figure 12. Varactor tripler designed using MultFreq (3 GHz to 9 GHz).

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